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# Comprehensive study of material dependency for silver based conductive glues

Andreas Schneider[a], Rudolf Harney[a], Severin Aulehla[a], Fatih Demiralp[a], Simon Koch[b], Jörg Scheurer[c], Christian Seeger[d]

[a]*International Solar Energy Research Center (ISC), Rudolf-Diesel-Str. 15, 78467 Konstanz, Germany*
[b]*Photovoltaik Institut Berlin AG, Wrangelstr. 100, 10977 Berlin, Germany*
[c]*Polytec PT GmbH, Polytecplatz 1-7, 76337 Waldbronn, Germany*
[d]*Bruker-Spaleck GmbH, Berneckstr. 72, 78713 Schramberg, Germany*

**Abstract**

This work is related to a comprehensive study on the material dependency for solar cell interconnection by means of epoxy based silver conductive glue (CG) and its effect on module reliability. The effect of power degradation for samples exceeding DH1000 was studied for various ribbon coatings, rear side AlAg silver pad pastes, amount of CG and for different encapsulation materials. We show that the choice of cell and module materials play a significant role in terms of electro-chemical corrosion. Cheap ribbon materials as non-coated copper ribbon were identified which lead to very positive damp heat results if used in combination with the right encapsulation materials. Special $R_{contact}$ samples did undergo more than 3000 hours of damp heat and proved that pure Cu ribbons without any coating performed almost the same as Ag coated ribbon and significantly better compared to Sn coated ribbon which typically fails for more than 1200 hours of DH. The speed of moisture ingress strongly impacts the corrosion process, hence specifically the rear contact is prone to degradation. We show that this process is even accelerated for larger amounts of dispensed CG. A study on various encapsulant materials showed that non coated Cu ribbon showed excellent results for TPO, TPO with embedded Al and Ionomer materials and acceptable results for Tectosil and EVA whereas Sn coated ribbon requires a TPO based material. DH testing proved that the choice of AlAg paste has a measurable effect on the electro-chemical corrosion and a minor impact on the CTM losses. Finally results for a new CG product development with superior peel strength and contact behavior are presented.


Peer-review under responsibility of the scientific committee of the SiliconPV 2014 conference

*Keywords:* Solar modules; conductive glue; ribbon; climatic testing; peel testing


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## 1. Introduction

Conductive glues offer major advantages in solar cell interconnection compared to the soldering process: Bow reduction due to reduced process temperature, contacting of solar cells without front busbars hence offering big saving potential in Ag metallization paste and the application of lead-free ribbons which are currently rarely used due to the by 50 Kelvin increased soldering temperature leading to increased cell breakage. Another major disadvantage of soldering is the incompatibility with cell interconnection of certain high efficiency cell designs as IBC cells. Currently stringer equipment suppliers are already or on its way to offer new stringers or modification for existing equipment to adapt for the glue application (dispensing or printing) and curing process. Specifically with new cell designs as IBC cells are on the rise to enter mass production this technique promises great advantages compared to soldering. This development comes along with strong price reductions for CG due to recent developments with less Ag filling. On the other hand only little or no information is available on how epoxy based silver CG reacts if combined with various materials as AlAg pastes, encapsulation materials and ribbon coatings. For this reason a vast material study was conducted under extended IEC testing conditions to help understanding and controlling the electrical corrosion effect which can only be seen once exceeding DH1000 hence being insensitive to IEC testing in certain respects [1, 2]. Furthermore was a new CG product with superior properties in terms of peel strength and cell to module losses evaluated. Both adhesives, SB1227 respective SB1242, are a product line which is distributed by Polytec PT GmbH and manufactured by Germany based SoltaBond GmbH.

## 2. Design of experiment

The material investigation should cover the main materials, which are responsible for electro-chemical corrosion or promoting the effect of degradation by water ingress and was performed partly on special contact resistance samples and on one-cell mini-modules. The study was divided into four parts:

- *Study of the $R_{contact}$ change during damp heat for Ag front busbar, AlAg rear pad and various ribbon coatings*
  To understand the effect and root causes of electro-chemical corrosion during damp heat in more detail $R_{contact}$ samples as shown in Fig. 1 were prepared: various ribbon (pure Cu ribbon, Cu ribbon with 100% Ag coating and Cu ribbon with 100% Sn coating), Ag front busbar as well as AlAg rear pad stripes were interconnected by CG (SB1227) and the total resistance change monitored during damp heat twice per week. In total 12 contact points between CG and sample material was established to increase the overall series resistance and allow for less measurement errors due to the small contact resistance of CG to material. The sample/glue interconnection was placed on a substrate (silicon wafer isolated by PET foil) and embedded between standard module glass and backsheet by EVA hence showing a standard module setup. Since the backside will see accelerated moisture ingress due to the large backsheet area the ribbon/glue interconnection was divided into two groups: facing the glass side (front side) and facing the backsheet (rear side). Several samples were processed for each material combination and exposed to 3000 hours of damp heat (85 degrees Celsius and 85% relative humidity).

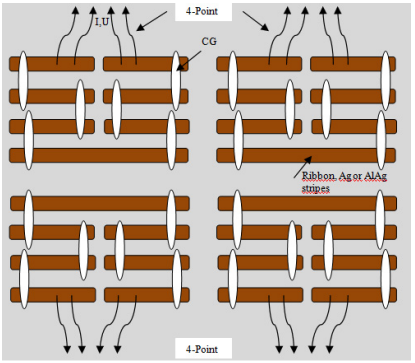


Fig. 1. $R_{contact}$ setup of samples used for the electro-chemical corrosion study.

- *Investigation of the material dependency of conductive glues in respect to electro-chemical corrosion for various encapsulation materials and ribbon coatings on module level*
  Water ingress is strongly depending on the backsheet water permeability as well on the encapsulation material properties. The water permeability for backsheet material is usually defined in grams per day and square meter and varies slightly from supplier to supplier. On the other hand do various encapsulation materials have different abilities to store water therefore it is expected that the choice of encapsulation material and backsheet influences the speed of electro-chemical corrosion. For this investigation three one-cell mini-modules were processed for each material group: TPO with supplier recommended backsheet, Tectosil with supplier recommended backsheet, Ionomer with supplier recommended backsheet, EVA with supplier recommended backsheet and TPO with an embedded Al layer in the backsheet as been typically used in thin film industry (as well high efficiency cell concepts). Furthermore the ribbon coating varied for each encapsulation material combination: pure Cu ribbon without any coating, Sn100 coated ribbon and Ag100 coated ribbon. The ribbon was attached to 6" mc standard industrial solar cells (exhibiting three continuous Ag front busbars and AlAg pads) by conductive glue (type Soltabond SB1227). To allow for comparable results ribbon width and thickness was the same for all ribbon beside the Ag100 coated ribbon with a significantly smaller cross section. As reference three soldered mini-modules with SnPbAg coated ribbon were processed for each encapsulation material combination. In total 60 mini-modules did undergo damp heat exposure for 3000 hours (85 degrees Celsius and 85% relative humidity). At intermediate intervals (1100, 1500 and 2000 hours) all samples were characterized by means of IV and Electroluminescence (EL). Additionally the data were used for calculating the individual cell to module losses.

- *Study of the effect of varying conductive adhesive application amount on degradation during damp heat exposure and its effect on peel force*
  In contrast to soldering the fundamental contacting behavior for conductive adhesive is completely different and the contacting quality and properties may differ with the amount of applied CG. This may relate to the effect of electro-chemical corrosion as well as on $R_{contact}$, hence the CTM losses. To understand this effect in more detail four one-cell mini-modules were processed for each CG variation. SnPbAg coated ribbon was attached to 6" mc standard industrial solar cells (exhibiting three continuous Ag front busbars and AlAg pads) by SB 1227 with varying amount of CG (10 mg, 20 mg, 30 mg and 40 mg per busbar). The same EVA and backsheet combination was used as for the previous experiments. Peel force was measured by using a Zwick 180° peel force device and 6 ribbons for each application amount and cell side for averaging used. The degradation effect due to corrosion was studied after 1000 and 2000 hours of DH by IV and EL. Since the amount of adhesive may also interfere with the adhesion between ribbon and cells busbar TC was conducted up to 300 cycles and samples characterized for electrical losses by means of IV and EL. Furthermore were the CTM losses determined.

- *Verification of degradation behavior for three different rear AlAg pastes*
  Contact resistance and adhesion of CG not only depend on the ribbon surface (coating) but also on the cells metallization pastes on front side (busbars) and rear side (pads). Since rear side AlAg pastes can be easily exchanged during solar cell processing in contrast to Ag pastes cells were processed (exhibiting three continuous Ag front busbars and AlAg pads) with three different AlAg pastes (the same Ag paste was used). SnPbAg coated ribbon was attached to busbars and pads by means of SB1227 and soldering as reference. For averaging four one-cell mini-modules were processed for each group (SB1227, soldering and AlAg pastes). CTM losses were determined to study the intrinsic losses due to differences in $R_{contact}$. Furthermore did all samples undergo DH3000 to study the effect on electro-chemical corrosion with intermediate and final IV and EL measurement (at 1000, 2000 and 3000 hours of DH). Peel force was measured by using a Zwick 180° peel force device.

## 3. Epoxy-based Ag conductive glues

Electrically conductive adhesives, resp. glues, (ECA's) are a well-known alternative to soldering in the microelectronic industry since a long time and are also used already in thin film PV industry. These adhesives are typically based on organic polymers, which are filled to a certain weight portion with electrically conductive particles. These filler particles are mainly silver based, because of its low electrical resistivity and its excellent

stability against oxidation. As a noble metal silver has a standard electrode potential of +0.80V and is therefore quite inert. But if silver comes into contact with metals with different standard electrode potentials contact corrosion could occur. This contact corrosion could be minimized if the difference of the standard potential of the two metals is small. If the ribbon coating e.g. consists out of tin or a tin based alloy, the risk of contact corrosion due to a quite huge difference in the standard potentials of silver and tin ($\Delta = 0.94$V) is high. In comparison to a tin coating, copper shows only a difference of 0.28V and therefore contact corrosion should be less. On the other side adhesive manufacturers could also integrate appropriate corrosion inhibitors in the adhesive formulation in order to prevent an oxidation of non noble metals. Standard isotropic conductive adhesives contain typically more than 70wt% of silver and show an electrical volume resistivity of at least $10^{-4}$ Ωcm. But due to the high and also very volatile silver price efforts are undertaken to reduce the absolute silver content by using e.g. silver coated particles or in general silver fillers with an improved electrical conductivity. The electrically conductive adhesives (SB1227, SB1242) mentioned herein, are based on epoxy resins. These adhesives have to be thermally cured with appropriate hardeners by a polyaddition reaction at temperatures of 150°C or higher. Within this curing reaction the adhesives change from a viscous paste into a solid polymer which goes along with volume shrinkage. The shrinkage is necessary to form an electrically conductive network. As epoxy based adhesives show a good thermal and chemical resistance, ECA's typically consist of this polymer base. Among this type of adhesive also acrylate and silicone based ECA's are commercially available, but show different drawbacks concerning process-ability or resistivity.

So far ECA's could be a real alternative for an interconnection technology for crystalline solar module manufacturing. If using adhesives for an electrical contact of the ribbons to the cell, no busbars and therefore less silver paste is needed. On the other hand adhesives offer an RoHS ("restriction of hazardous substances") compatibility, because of lead- and flux-free, interconnection technology. Furthermore compared to soldering the curing of adhesives is done at lower temperatures, which means less thermo-mechanical stress, cell bow or micro cracks. Due to the organic polymer matrix of the ECA's it is also possible to integrate a certain flexibility into the formulation in order to absorb, respectively to reduce mechanical stress caused by the different thermal expansion coefficients (silicon, copper, silver, glass, EVA etc.).

## 4. Results

### *4.1. Study of the $R_{contact}$ change during damp heat for Ag front busbar, AlAg rear pad and various ribbon coatings*

As an example for all samples the change in electrical resistance between Ag front busbar stripes interconnected by means of CG SB1227 over damp heat exposure time is shown in Fig. 2 (left). The data can be nicely fitted by an exponential function as shown in formulae (1). Fig 2 (right) also shows the typical recovery of resistance after initial increase, meaning reduction in resistance up to a threshold value from which the resistance steadily increases.

$$y = y_0 + A \cdot e^{R_0 \cdot x} \tag{1}$$

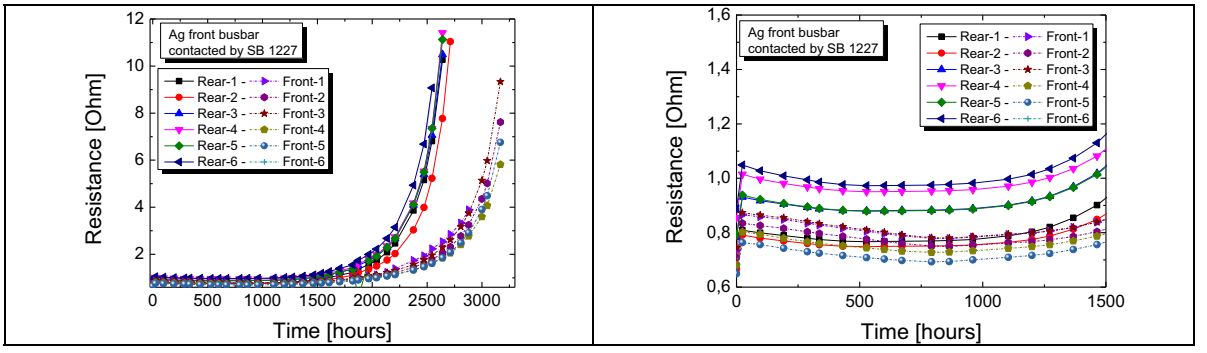


Fig. 2. (a) resistance change for Ag front busbar samples; (b) cutout for resistance change up to 1500 hours.

The fitted parameters for $y_o$, $A$ and $x$ are displayed in Table 1. The resistance change in percent after 1000 hours of damp heat ($\Delta R$ *1000 hours*) is shown as a reference for typical IEC testing standards. Furthermore are the hours displayed where the maximum recovery (meaning the minimum) in resistance was observed and the drop in percent of the resistance (right column of Table I, labeled as $time_{Rmin}$ and $Rmin_{@recovery}$).

Table 1. Fitted data according to formulae (1), resistance drop after 1000 hours and time for maximum resistance recovery and resistance change.

| Samples | $y_o$ [Ω] | A [Ω] | $R_0$ | ΔR (1000hrs) [%] | $time_{Rmin}$ [hrs] / $Rmin_{@recovery}$ [%] |
|---|---|---|---|---|---|
| Ag BB Front | 0.80±0.03 | 3.81E-04±1.16E-04 | 3.06E-03±9.92E-05 | 6.96 | 828±39 / -9.75±0.67 |
| Ag BB Rear | 0.88±0.04 | 5.02E-04±1.39E-04 | 3.70E-03±1.07E-04 | 12.51 | 528±0 / -6.00±0.81 |
| AlAg Pad Front | 1.23±0.01 | 2.8E-03±1.0E-03 | 2.11E-03±1.31E-04 | 19.15 | 882±178 / -3.71±1.83 |
| AlAg Pad Rear | 1.06±0.03 | 2.88E-04±1.15E-04 | 3.41E-03±1.37E-04 | 15.32 | 720±48 / -3.12±0.20 |
| Cu100 Ribbon Front | 0.28±0.01 | 3.15E-03±8.91E-04 | 1.66E-03±8.82E-05 | -21.18 | 816±0 / -16.84±0.81 |
| Cu100 Ribbon Rear | 0.23±0.01 | 7.79E-03±1.82E-03 | 1.26E-03±7.20E-05 | -6.91 | 336±0 / -5.13±0.31 |
| Sn100 Ribbon Front | -0.51±0.74 | 8.27E-01±6.47E-01 | 1.09E-03±4.75E-04 | 471.80 | 0±0 / 0±0 |
| Sn100 Ribbon Rear | 2.10±0.27 | 1.67E-02±2.20E-02 | 4.85E-03±1.09E-03 | 432.41 | 96±34 / -5.64±7.97 |
| Ag100 Ribbon Front | 0.38±0.04 | 1.72E-05±1.80E-05 | 3.75E-03±3.27E-04 | -23.47 | 816±0 / -20.07±0.88 |
| Ag100 Ribbon Rear | 0.59±0.09 | 5.38E-08±7.47E-08 | 7.64E-03±5.57E-04 | -13.40 | 528±68 / -9.75±0.19 |

Since the fitted data for $R_0$ is of the same order of magnitude the focus is now on the parameter $A$. This parameter clearly shows the largest value hence the strongest degradation for Sn100 coated ribbon and the smallest value for Ag100 coated ribbon. Pure Cu ribbon shows $A$ values lying in between these for Sn100 and Ag100 coated ribbon. Also does the parameter $A$ indicate larger values for AlAg rear pads compared to Ag front busbars indicating a larger electro-chemical corrosion for rear side AlAg pads with conductive glues. The front setup reveals for all materials a maximum recovery time $time_{Rmin}$ of approximately 800 hours beside the Sn100 coated ribbon with no recovery time due to the reason of very strong electro-chemical corrosion. The value for the rear setup is significantly smaller if compared to the front setup due to the larger water ingress of the backsheet. This also can be seen in the maximum drop of the resistance if compared to its initial value $Rmin_{@recovery}$. The resistance change after 1000 hours, if compared with its initial value, is extremely high for the Sn100 coated ribbon, exceeding +400% for both setups. Ag100 coated and pure Cu ribbon show an up to 20% reduced value for the resistance. The resistance increase for the AlAg rear pads are significantly larger than the increase for the Ag front busbar samples.

The data points out that either Ag100 coated ribbon or pure Cu ribbon is the best choice for ribbon material for the epoxy based silver containing SB1227 conductive glue. Furthermore is Sn100 coated ribbon no choice due to its large inherent electro-chemical corrosion. Both, Ag front busbars and AlAg rear pads do exhibit degradation with increasing effects for larger water ingress. Furthermore do the results indicate that typical IEC61215 standards for damp heat procedure may not be well specified for solar modules exhibiting cells interconnected by means of CG. At least the exposure time shall be subject of reconsideration.

### *4.2. Investigation of the material dependency of conductive glues in respect to electro-chemical corrosion for various encapsulation materials and ribbon coatings on module level*

On module level further effects will have an influence on the electro-chemical corrosion: water permeability of backsheet, water storage capacity of encapsulant and pH value of the sandwich after encapsulation in combination with heat and humidity during damp heat test. Fig. 3 shows the $P_{mpp}$ loss of mini-modules interconnected by means of SB1227 and Sn100, Ag100 coated and pure copper ribbon for various module encapsulation (backsheet and encapsulant) materials. For reference standard SnPbAg coated ribbon was soldered to cells front and rear side.

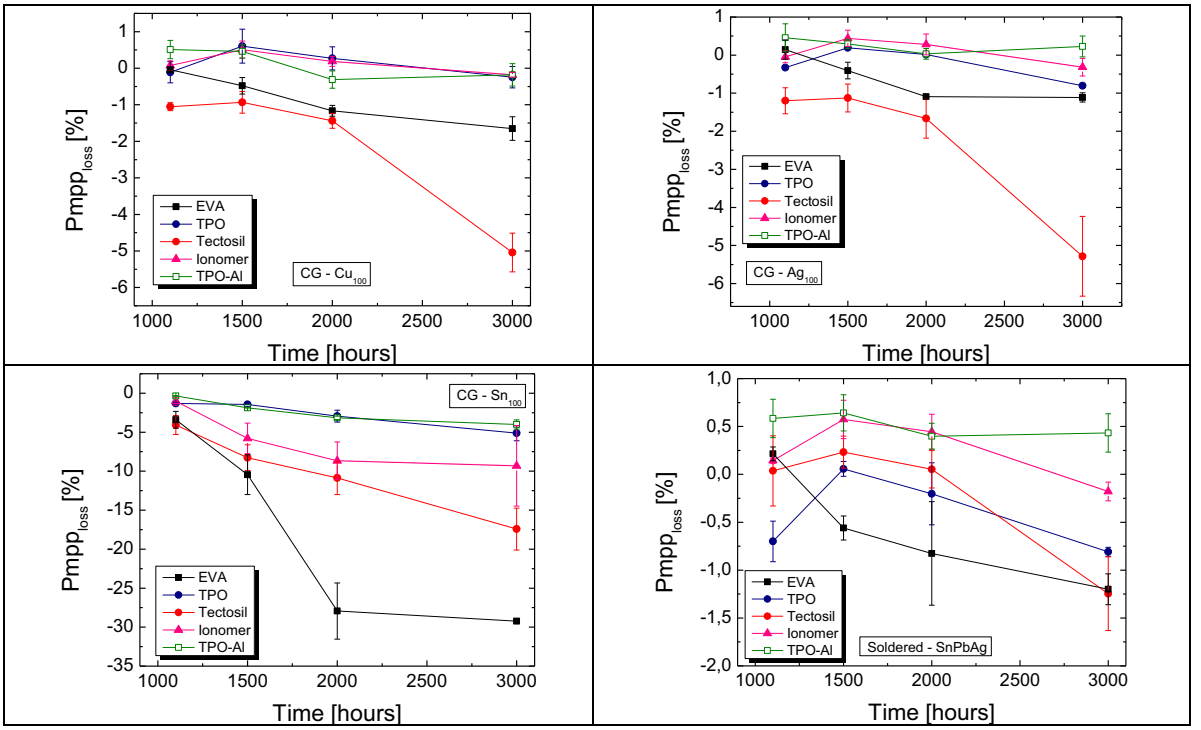


Fig. 3. Power loss after damp heat exposure for various ribbon and encapsulation materials.

As previously found for the special contact resistance samples Sn100 coated ribbon shows the worst performance for all encapsulation materials. Nonetheless would all samples pass DH1000 according to the +/-5% rule of the IEC testing standards. Standard EVA shows 30% power losses after DH2000, Tectosil 10% and Ionomer 9%. Only TPO material exhibits losses of 3% with slightly better performance after DH3000 for the Al containing backsheet. The losses for Ag100 coated ribbon are well below 1.2% after DH3000 for all encapsulation materials beside the Tectosil material. TPO in combination with the backsheet with Al embedded shows no losses at all and negligible degradation for the Ionomer material combination. Losses of only 0.2% were found for the pure copper ribbon for TPO based and Ionomer materials. EVA exhibits degradation in $P_{mpp}$ of 1.7% and Tectosil of 5%. For the soldered references (SnPbAg coated ribbon) best results after DH3000 were achieved for TPO and Ionomer material with either no or moderate power loss of less than 1%. Only 1.3% loss can be reported for Tectosil and EVA. The results clearly show that electro-chemical corrosion has the least impact on pure copper ribbon and Ag100 coated ribbon and the worst effect on Sn100 coated ribbon. The encapsulation material has a strong influence on the corrosion speed with worst performance for the standard EVA material. For all samples beside the Tectosil material the loss in $P_{mpp}$ is attributed to a loss in fill factor, proving that the resistance is the main cause for the losses. Only the Tectosil material combination shows for all ribbon types significant losses attributed to $I_{sc}$, $V_{oc}$ and $FF$.

For future evaluation the optical appearance of samples after damp heat testing is important to know. Table 2 shows the discoloration of encapsulant and ribbon surface (plus ribbon surrounding). The least discoloration was found for the TPO materials, followed by Ionomer. Worst discoloration is seen for EVA and Tectosil. Even 100% Ag coated ribbon shows a discoloration on the ribbon surface for TPO and Tectosil. The strongest and worst ribbon color change was discovered for Tectosil on pure copper ribbon.

Table 2. Discoloration of encapsulant and ribbon surface after 3000 hours of damp heat exposure time.

| Samples | Ag100 | Cu100 | Sn100 | Soldering SnPbAg |
|---|---|---|---|---|
| | Encapsulant / Ribbon | Encapsulant / Ribbon | Encapsulant / Ribbon | Encapsulant / Ribbon |
| EVA | Slight / No | Slight / Strong | Slight / No | Slight / No |
| TPO | No / Slight | No / No | No / No | No / No |
| TPO with Al | No / No | No / Medium | No / No | No / No |
| Ionomer | No / No | No / Medium | No / No | No / Slight |
| Tectosil | Medium / Medium | Medium / Very strong | Medium / No | Medium / No |

The CTM losses for the short circuit current and the fill factor were evaluated for the ribbon of identical cross section (SnPbAg, Sn100 and pure Cu) and are displayed in Table 3. The other characteristic cell and module data is omitted since the subject of the study is on contacting behavior and transmission losses. As expected the difference for $I_{sc}$ for the same encapsulation material but varying interconnect (soldered SnPbAg, glued Cu and Sn100 coated ribbon) is negligible. Large variations exist for different encapsulation materials with smallest losses for one TPO material and the EVA. Largest losses in transmissivity were found for the other TPO material, followed by Tectosil and Ionomer. This information has to be taken into consideration for future application of CG with best performing materials during climatic testing and to optimize the overall CTM losses. The *FF* losses are least for the soldered contact for EVA, TPO and TPO-Al material. Tectosil and Ionomer showed smaller or equal losses for the pure copper ribbon if compared to soldering. The Sn100 coated ribbon performed worst with largest *FF* losses. Due to the same cross section of all ribbon the main effect stems from the contact resistance between ribbon and busbar for soldering and gluing and a small impact of line resistance for the glued interconnection. Taking this information into account glued non-coated Cu ribbon showed excellent performance with losses being close to the soldered contact.

Table 3. CTM data for $I_{sc}$ and FF for soldered SnPbAg, CG connected to pure Cu and Sn100 coated ribbon for various encapsulation materials.

| Material | $I_{sc}$-SnPbAg-Solder | $I_{sc}$-Cu-CG | $I_{sc}$-Sn-CG | FF-SnPbAg-Solder | FF-Cu-CG | FF-Sn-CG |
|---|---|---|---|---|---|---|
| | [A] | [A] | [A] | [%] | [%] | [%] |
| EVA | -1.61±0.09 | -1.56±0.07 | -1.84±0.28 | -3.74±0.07 | -4.25±0.07 | -4.45±0.08 |
| Tectosil | -2.39±0.47 | -2.41±0.13 | -2.30±0.37 | -4.17±0.13 | -4.03±0.10 | -4.50±0.08 |
| Ionomer | -1.72±0.24 | -1.68±0.19 | -1.38±0.16 | -4.00±0.12 | -4.04±0.04 | -4.30±0.01 |
| TPO | -0.96±-0.00 | -1.02±0.23 | -0.81±0.22 | -3.85±0.02 | -4.34±0.01 | -4.11±0.17 |
| TPO - Al | -2.52±0.01 | -2.51±0.01 | -2.50±0.04 | -3.84±0.09 | -4.26±0.12 | -4.36±0.09 |

Previous experiments indicated that the speed of corrosion for rear AlAg to ribbon contact is significantly exceeding the degradation of the front Ag to ribbon contact during DH [2]. To further study this effect samples were processed allowing for increased moisture ingress to only one cell side during DH testing according to Fig. 4 (left).

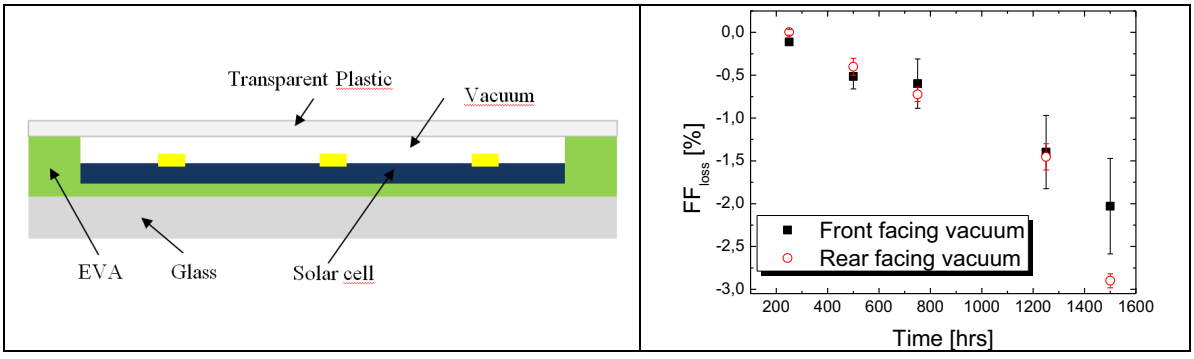


Fig. 4. Sample layout to check for corrosion speed on front and read side of solar cell.

Either the front or rear side of the cell is surrounded by a strong water barrier by a glass / EVA layer (the solar cell side facing the glass is changed) whereas the other side was exposed to vacuum and a transparent plastic sheet designed for solar applications with higher water ingress specification. Samples were initially IV measured and exposed to 1500 hours of damp heat. The fill factor loss displayed in Fig. 4 (right) reveals a significant drop for samples passing 1200 hours of damp heat strongly pronounced for the rear contact. This data confirms that the rear side AlAg paste is more sensitive to electro-chemical corrosion than the front side Ag contact.

### *4.3. Study of the effect of varying conductive adhesive application amount on degradation during damp heat exposure and its effect on peel force*

Because of the rather complicated contact mechanism of silver flakes during CG curing and its interaction with the cells ribbon larger amounts of dispensed CG per busbar lead to a loss in fill factor as can be seen on mini-modules in Table 4. The line resistance of intrinsic CG is significantly increased with the CG thickness which reduces the fill factor. At the same time it was observed that electro-chemical corrosion (for Sn based ribbon coating) strongly increases for larger CG amounts only after DH1000 and even stronger pronounced after DH2000.

Table 4. FF change (cell to module), power losses after TC and DH testing as well peel strength for front and rear side for various CG amount.

| CG Amount [mg/BB] | ΔFF [%] Cell-to-Module | $\Delta P_{mpp}$ [%] TC200 | $\Delta P_{mpp}$ [%] TC300 | $\Delta P_{mpp}$ [%] DH1000 | $\Delta P_{mpp}$ [%] DH2000 | $Peel\ Strength_{front}$ [N] | $Peel\ Strength_{rear}$ [N] |
|---|---|---|---|---|---|---|---|
| 10 | -4.3±0.1 | -0.36±0.06 | -0.33±0.35 | -0.52±0.32 | -8.63±2.22 | 0.12±0.07 | 0.15±0.07 |
| 20 | -4.3±0.1 | -0.41±0.10 | -0.44±0.12 | -0.69±0.36 | -8.68±5.11 | 0.17±0.06 | 0.19±0.06 |
| 30 | -4.4±0.1 | -0.38±0.15 | -0.27±0.18 | -0.98±0.08 | -19.63±11.32 | 0.19±0.05 | 0.19±0.08 |
| 40 | -4.5±0.2 | -0.64±0.05 | -0.50±0.05 | -0.85±0.33 | -21.35±3.58 | 0.31±0.07 | 0.25±0.06 |

Contrary to the assumption that larger amounts of CG will lead to more stability during thermo-cycling the results after 200 cycles of TC reveal an almost double loss for samples with 40 mg/BB dispensed CG compared to 10 mg/BB. This also cannot be explained by the peel strength since larger amounts of CG lead to significantly larger peel strength as can be seen in Table 4 for front and rear side. It has to be noted that peel strength is far below 1 N nonetheless not affecting the samples to pass 200 cycles of thermo-cycling or more as previously reported in [2].

By using a larger amount of ECA in between cell and ribbon, the bond thickness of ECA is also increased. This goes along with an increased number of electrical $R_{contact}$ between the single filler particles, because the polymer matrix by itself around each particle is electrically insulating. Therefore the resistance of the bond line is increased which ends up in a reduction of the *FF*. One possible reason for a higher power loss after DH if using higher amounts of ECA per busbar, could be that at the same time more humidity penetrates into the bond line and influences the velocity of the contact corrosion due to a change of the ion conductivity of the polymer matrix.

### *4.4. Verification of degradation behavior for three different rear AlAg pastes*

Paste rheology of Ag front and AlAg rear pastes may have a significant effect on $R_{contact}$ as well on the electro-chemical corrosion during DH test if connected with ribbon by means of CG. Three different commercially available rear side AlAg pad pastes (A, B, C) were investigated for differences in CTM losses, peel strength and power loss during DH exposure and compared to soldered references. Damp heat testing of EVA based mini-modules exhibit that all CG samples show larger $P_{mpp}$ losses for more than 1000 hours of damp heat. Interestingly to note that even for soldered references significant differences in performance can be reported (see Table 5).

After 2000 hours of DH we can see a significant loss in $P_{mpp}$ if using SnPbAg coated ribbons and contacting different AlAg rear pastes on crystalline cells. In contradiction to pure Ag front paste another non noble metal (Al) is integrated into the rear side stack. This stack is consisting out of AlAg (paste) - Ag (adhesive) – SnPbAg (ribbon coating) – Cu (ribbon core), and maybe some other not known metallic ingredients in the rear side AlAg paste like

e.g. lead or cadmium. The standard electrode potential of aluminum is -1.66V due to its non noble character. By using a silver filled ECA, contact corrosion could occur because of a huge difference in the standard electrode potential of silver and aluminum ($\Delta$ = 2.44V). How far the pH-value of the used hardener in the ECA is influencing this corrosion of the aluminum containing paste, respectively of tin coated ribbons on the cell front side has to be investigated in more detail by choosing different ECA's based on different hardener types.

Table 5. $P_{mpp}$ degradation and CTM losses for three different AlAg pad pastes during DH3000 testing.

| AlAg Paste | ΔFF CTM [%] CG | ΔFF CTM [%] Soldered | $\Delta P_{mpp}$ [%] Soldered DH1000 | $\Delta P_{mpp}$ [%] CG DH1000 | $\Delta P_{mpp}$ [%] Soldered DH2000 | $\Delta P_{mpp}$ [%] CG DH2000 | $\Delta P_{mpp}$ [%] Soldered DH3000 | $\Delta P_{mpp}$ [%] CG DH3000 |
|---|---|---|---|---|---|---|---|---|
| A | -4.76±0.20 | -4.49±0.17 | 0.0±0.0 | 0.0±0.1 | -0.4±0.0 | -7.7±1.9 | -0.8±0.0 | -16.7±6.5 |
| B | -4.47±0.16 | -4.75±0.33 | -1.0±1.3 | 0.7±3.5 | -1.7±1.2 | -6.7±-6.1 | -3.2±0.5 | -21.9±18.2 |
| C | -4.54±0.03 | -4.62±0.06 | 0.0±0.2 | -0.4±0.0 | -0.1±0.1 | -4.4±0.6 | -2.0±1.6 | -15.6±4.8 |

The rather large CTM losses are a reason of the specific one-cell mini-module design: The glass size is 20x20 $cm^2$ hence leading to large series resistances losses coming along with a reduction in *FF* due to the cell exceeding ribbon by more than 4 cm on each side. The additional resistance brought in by the longer ribbon acts as offset and will have no influence on the relative power change evaluation. For the soldered references we see differences of 3% - 6% in *FF* for various AlAg pastes and 2% - 6% for the CG interconnected ribbons hence both interconnection types exhibiting almost the same losses. No differences were measured in peel strength for CG interconnected ribbon for all three AlAg pastes.

## 5. New CG developments

Previous investigation revealed certain weak points for the existing SB1227 conductive glue: very small peel strength and depending on the AlAg paste larger CTM losses if compared to the soldering process. To tackle these problems Soltabond has put strong accentuation on developing a new epoxy-based Ag conductive glue. The development leads to a new product which is now commercially available under the brand Soltabond SB1242.

In contrast to SB1227 the new product was improved concerning peel strength by using a different epoxy polymer matrix. On the other side the fast curing schedule of SB1227 should not be decelerated in order to replace industrial soldering processes in respect of cycle time. Due to economical reasons SB1242 was also reduced in respect to the silver content about nearly one third in comparison to the well established SB1227 by choosing more efficient electrically conductive fillers. In previous investigations no performance differences could be detected within one-cell mini-modules if using SB1227 or SB1242, even after ageing process in damp heat for 1500h.

Five one-cell mini-modules with ribbon interconnected by means of SB1242 and five with ribbon interconnected by soldering were processed using the same standard materials based on EVA as described before. The ribbon for the CG attachment was Ag100 coated of width 1.5 mm and thickness 0.2 mm. Ribbon of the same width and thickness but SnAg coated was used for the soldered references. Peel strength for the new conductive glue reveals excellent results of 1.3 N and 1.7 N for front, resp. rear contact and shows an increase of several hundred percent if compared to the SB1227 product (see Table 6). Furthermore is the cell to module loss absolutely comparable to the soldered references. Tested product stability during damp heat testing revealed very stable results with negligible differences between soldered contact and contacts established by means of conductive glue.

Table 6. CTM loss for FF and $P_{mpp}$, peel strength for front and rear contact and power loss after DH1500 for SB1242 and soldered references.

| Sample | ΔFF CTM [%] | $\Delta P_{mpp}$ CTM [%] | $\Delta P_{mpp}$ [%] DH1500 | $\text{Peel Strength}_{front}$ [N] | $\text{Peel Strength}_{rear}$ [N] |
|---|---|---|---|---|---|
| SB1242 | -5.00±0.10 | -6.56±0.18 | -1.45±0.27 | 1.31±0.15 | 1.67±0.35 |
| Solder Reference | -5.01±0.40 | -6.75±0.24 | -1.21±0.45 | 2.67±0.44 | 2.26±0.43 |

## 6. Conclusion

The paper conducts a comprehensive study on the material dependency of conductive glue application in terms of its sensitivity to chemical corrosion, specifically during damp heat testing. Various encapsulation materials in combination with differently coated solar ribbon were investigated for its influence on cell to module losses and degradation effect during damp heat. In addition the impact of increasing conductive glue amount and three different rear pad AlAg pastes in terms of contacting quality of ribbon to glue and cell were in depth analyzed. Several ways on how to reduce or eliminate completely the electro-chemical corrosion effect were presented hence making the conductive glue application a reliable interconnection technique.

It has been shown that Sn100 coated ribbon is no choice for most of the encapsulation materials available on the market whereas Ag100 coated ribbon provides the most stable interconnection for all materials during climatic testing. For non-coated copper ribbon only one encapsulation material showed larger losses after 3000 hours of damp heat and only minor losses for all other materials. This result is specifically important since non-coated copper ribbon provides the cheapest choice of electrical interconnection. Certain discoloration which has been observed after damp heat testing on the ribbon surface and encapsulant material may be omitted by a cheap and easy to apply thin non-metallic protective coating on the ribbon as been already used for conductive backsheets. The data proved that the ribbon to AlAg pad connection by CG is more prone to electro-chemical corrosion than the ribbon to front side Ag busbar. Different AlAg products have a minor influence on the corrosion effect nonetheless even for soldered ribbon interconnection significant differences in performance after DH3000 are observed. Increased amount of applied conductive adhesive lead to larger power losses during damp heat and a stronger pronounced initial cell to module loss due to a larger series resistance caused by the thicker CG layer.

Results for CTM losses and peel strength for a new conductive glue product which just entered the market confirmed very high peel strength values ranging between 1.3 N and 1.7 N hence fulfilling typical industrial requirements of 1 N and showing absolutely comparable CTM values. Furthermore reliable performance during DH1500 was proven for Ag100 coated ribbon.

With the data of this study on hand recommendations for future conductive glue application on crystalline silicon solar cells can be given: Firstly, since non-coated copper ribbon shows excellent performance this product may offer the best compromise between price and reliability if certain measures as protective coating to prevent discoloration are taken. Secondly, the climatic testing standards, specifically those related to simulate moisture ingress, have to be re-evaluated in terms of exposure time for the application of CG to find potential electro-chemical corrosion on module level. Thirdly, special attention has to be paid on the amount of applied CG and the right choice of rear pad AlAg cell pastes. Last but not least the right choice of the encapsulation material to allow for least cell to module losses in terms of light transmissivity as well on its influence on electro-chemical corrosion has to be taken. With this information on hand conductive adhesive materials may have the break-through in cell interconnection, specifically as recent CG developments show a strong price reduction as well large peel strength and absolutely comparable cell to module losses compared to soldering.

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## References

[1] D. Lu, C. P. Wong. A Study of Contact Resistance of Conductive Adhesives Based on Anhydride-Cured Epoxy Systems. IEEE Transactions on Components and Packaging Technologies 2000; Vol. 23; No.3.

[2] A. Schneider, R. Harney, S. Aulehla, E. Lemp, S. Koch. Progress in interconnection of busbar-less solar cells by means of conductive gluing. Energy Procedia 2013. Vol. 38.